PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

SOAR Optical Imager

Alistair R. Walker, Maxime Boccas, Marco Bonati, Ramon Galvez, Manual Martinez, et al.

Alistair R. Walker, Maxime Boccas, Marco Bonati, Ramon Galvez, Manual Martinez, Patricio Schurter, Ricardo E. Schmidt, Michael C. Ashe, Francisco Delgado, Roberto Tighe, "SOAR Optical Imager," Proc. SPIE 4841, Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, (7 March 2003); doi: 10.1117/12.457977

SPIE.

Event: Astronomical Telescopes and Instrumentation, 2002, Waikoloa, Hawai'i, United States

The SOAR Optical Imager

Alistair R. Walker[a], Michael Ashe[b,c], Maxime Boccas[d], Marco Bonati[e], Francisco Delgado[a], Ramon Galvez[a], Manuel Martinez[a], Patricio Schurter[a], Ricardo Schmidt[a], and Roberto Tighe[a]

[a]Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory
[b]Imaginetics, Inc.
[c]Southern Astrophysical Research (SOAR) Corp.
[d]Gemini Observatory
[e]Department of Astronomy, Caltech

ABSTRACT

The SOAR Optical Imager (SOI) is the commissioning instrument for the 4.2-m SOAR telescope, which is sited on Cerro Pachón, and due for first light in April 2003. It is being built at Cerro Tololo Inter -American Observatory, and is one of a suite of first-light instruments being provided by the four SOAR partners (NOAO, Brazil, University of North Carolina, Michigan State University). The instrument is designed to produce precision photometry and to fully exploit the expected superb image quality of the SOAR telescope, over a 6x6 arcmin field. Design goals include maintaining high throughput down to the atmospheric cut-off, and close reproduction of photometric passbands throughout 310-1050 nm. The focal plane consists of a two-CCD mosaic of 2Kx4K Lincoln Labs CCDs, following an atmospheric dispersion corrector, focal reducer, and tip-tilt sensor. Control and data handling are within the LabVIEW-Linux environment used throughout the SOAR Project.

Keywords: Instrumentation, imaging, CCDs

1. INTRODUCTION

The 4.2-m SOuthern Astrophysical Research (SOAR) telescope is sited on the northeast spur of Cerro Pachón, Chile, a few hundred meters from the 8-m Gemini South telescope. Its attributes have been discussed in detail elsewhere[1]; in summary, it is a smaller version of the 8 -m Gemini and VLT telescopes, with thin meniscus primary actively controlled. Both telescope and facility are optimized to delivery superb optical performance over a relatively small (~10 arcmin diameter) field. The telescope optical configuration is an F/16 Ritchey-Chrétien design for use over the wavelength range 300-2,500 nm, with instruments sited at the two Nasmyth platforms and up to three bent-Cassegrain stations. It can thus accommodate a large instrument complement simultaneously, and in addition has the capacity and interfaces needed to allow installation of Gemini facility instruments. Each focal station incorporates a fast CCD guider that drives the telescope tertiary mirror at up to 50 Hz in tip-tilt mode. The telescope is scheduled to reach first light in April 2003, with the SOAR Optical Imager (SOI) as commissioning instrument.

2. DESIGN PARAMETERS

The principal SOAR image specification is that telescope and facility induced image blur should not exceed 0.18 arcsec full width at half-maximum intensity (fwhm). This specification was derived from measurements of the 10^{th}-percentile seeing on Cerro Pachon as 0.30 arcsec fwhm, and the desire that the telescope plus facility should not degrade this figure by more than 10%. Instruments are allowed a similar budget, i.e. the SOI is not allowed by itself to introduce more than 0.18 arcsec of image blur, at the zenith., over its full passband of 310 -1050 nm. SOAR instruments are also required to exploit as much of the 10 arcmin diameter field as possible. The SOAR Science Advisory Committee decided on the following set of requirements for the SOI, given that SOAR's strength would be high image-quality over a small field, and that optimization in the blue-UV would allow exploitation of an important region at least competitively with the 8-m telescopes:

- Top-Level requirements

Instrument Design and Performance for Optical/Infrared Ground-based Telescopes,
Masanori Iye, Alan F. M. Moorwood, Editors, Proceedings of SPIE Vol. 4841 (2003)

- Image scale 0.08 arcsec/pixel
- Field of view 6x6 arcmin
- Atmospheric Dispersion Corrector (ADC) to correct wavelengths longer than 320 nm
- At least six parfocal filters
- Instrument to produce less than 0.15 arcsec image degradation at 550 nm

• Additional requirements

- On-board tip-tilt sensor
- Low scattered light
- Low heat leak
- At least 30 hours cryogen hold time

• Schedule requirement

- SOI to be first light instrument
- SOI to be sited at a bent-Cassegrain port

This set of requirements produced the following concept:

- Linear ADC comprising two fused silica prisms, and F/16:F/9 focal reducer
- Integral instrument rotator
- Twin filter wheels, modular, each 5-position
- Fast linear shutter
- 4Kx4K mosaic of two UV-optimized Lincoln Labs CCDs
- Pick-off and stage for Marconi CCD-39 fast guider
- SDSU-2 (Leach) controllers for both science and guider channels
- LabVIEW/Linux software environment

Figure 1: The SOAR Optical Imager. The interface to the telescope is the left-most flange of the braced tubular structure. The latter houses the two prisms of the atmospheric dispersion corrector. At its right-hand end is the rotator, which supports all the hardware to its right, plus the focal reducer optics. To the right of the rotator is found the filter, guider, and shutter box, to which is mounted the liquid-nitrogen cooled dewar, with a SDSU-2 (Leach) CCD Controller in front. Not shown in this picture is a second SDSU-2 Controller that is mounted behind the dewar, the external parts of the guider assembly, or the cable wrap assembly.

The instrument concept was approved by the SOAR Board in November 1998. The SOI passed conceptual design review in April 1999 and a pre-fabrication review in December 2000. It is due to be delivered to SOAR in October 2002. The partially-assembled instrument is shown in Figure 1, mounted on its handling cart.

3. OPTICAL DESIGN

The SOAR bent-Cassegrain position throws the telescope focus more than 2-m beyond the telescope structure, hence there is ample room to fit both an ADC and focal reducer optics in the converging F/16 beam. The two-prism linear ADC design adopted for the FORS instrument on the VLT[2] is an attractive alternative to the traditional double pair of zero-deviation rotating prisms[3], where space permits and the optical input beam is relatively slow. To preserve throughput to 320 nm the rotating ADC design requires use of fused silica and CaF2 glasses, the latter is difficult to produce in the large diameter required, and is a delicate material to work with. No one to our knowledge has ever built such an ADC, and we therefore chose the linear ADC design.

The linear 'trombone-like' ADC design is particularly suited for an alt-azimuth telescope as the angle between the image plane (i.e. the telescope altitude plane) and the atmospheric dispersion axis remains constant for all zenith distances, thus avoiding the need for prism rotation. Our ADC consists of a pair of fused silica prisms with the same apex angle and a constant 180 deg. orientation offset. The forward prism corrects the atmospheric dispersion by moving longitudinally in the beam, and the fixed prism corrects the image plane tilt. An image shift occurs depending on the prism separation, this can easily be accounted for in the telescope pointing model.

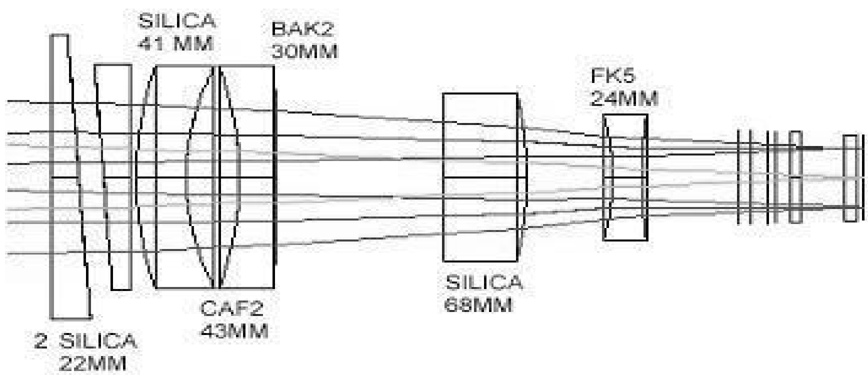

Figure 2: SOI Optical Design, including ADC. From left to right are the two prisms of the ADC, shown in position corresponding to the telescope at zenith, then the cemented triplet, then two singlets. The two alternative filter positions, the shutter, and the plane dewar window are indicated on the right. Labels indicate material and maximum thickness. Filters can be cemented combinations of Schott glasses, or interference filters. The dewar window is UV-grade fused silica, 10 mm thick.

The focal reducer optical design is an adaptation of an original concept by Gilberto Morretto, the concept consists of a 6-element F16 to F/9 reducer and field corrector, producing a global EE80 (80% encircled energy) diameter < 0.31 arcsec in each of the U,V,B,R,I broadband filters (typically 80-140 nm wide, 365-1000 nm center-wavelength range) over a flat 10x10 arcmin field. This original design was iterated in order to

- increase back-focal distance to accommodate tip-tilt guider pick-off
- include space for dual filter wheels and the dewar window
- decrease element thickness for ease of fabrication and improve UV transmission
- re-organize so that the single CaF2 element is encapsulated
- include the ADC in the design
- relax the field of view size from 10x10 arcmin to the required 6x6 arcmin

The image specification given above was expanded to

- FWHM < 0.18 arcsec at zenith (equivalent to EE80 < 0.27 arcsec)
- FWHM < 0.34 arcsec at zenith distance 70 deg. (equivalent to EE80 < 0.51 arcsec)

when imaging through astronomical broadband filters. The optical arrangement is shown in Figure 2 . Coatings on all exterior optics are Magnesium Fluoride overcoated with solgel[4], while the triplet is bonded using Corning Sylguard 184 transparent silicone. Throughput as a function of wavelength is shown in Figure 3. The design met the image specification at all wavelengths, as an example through a broadband V filter (500-600 nm) the FWHM at zenith is 0.12 arcsec, and at zenith distance 70 degrees a FWHM of 0.29 arcsec is achieved.

The design was subjected to four additional analyses. The cemented triplet was subjected to a thermal analysis, considering a temperature variation of –5C to +20C. For the fused silica-CaF2 interface, which is the most critical, we calculated that the compressive shear is entirely absorbed by the cement, and not in the glass. The maximum stress occurring in the cement is less than the shear elastic limit. The second test involved looked at the optical performance over the temperature range –5C to 20C using Zemax; no image degradation occurs.

We also performed a tolerance analysis and, as expected given the slow beam, there are no excessive mechanical demands on tilts, spacings and decentering. Finally a ghost analysis was performed; ghosts were s imulated both by ray tracing and using the Zemax ghost focus generator. There is no "sky concentration" effect, due to lack of any short radius of curvature element close to the focus. Considering the case of retro-reflection of incident light off the CCD surface, the worse case comes from the immediate reflection off the adjacent dewar window, 6mm away. The ghost

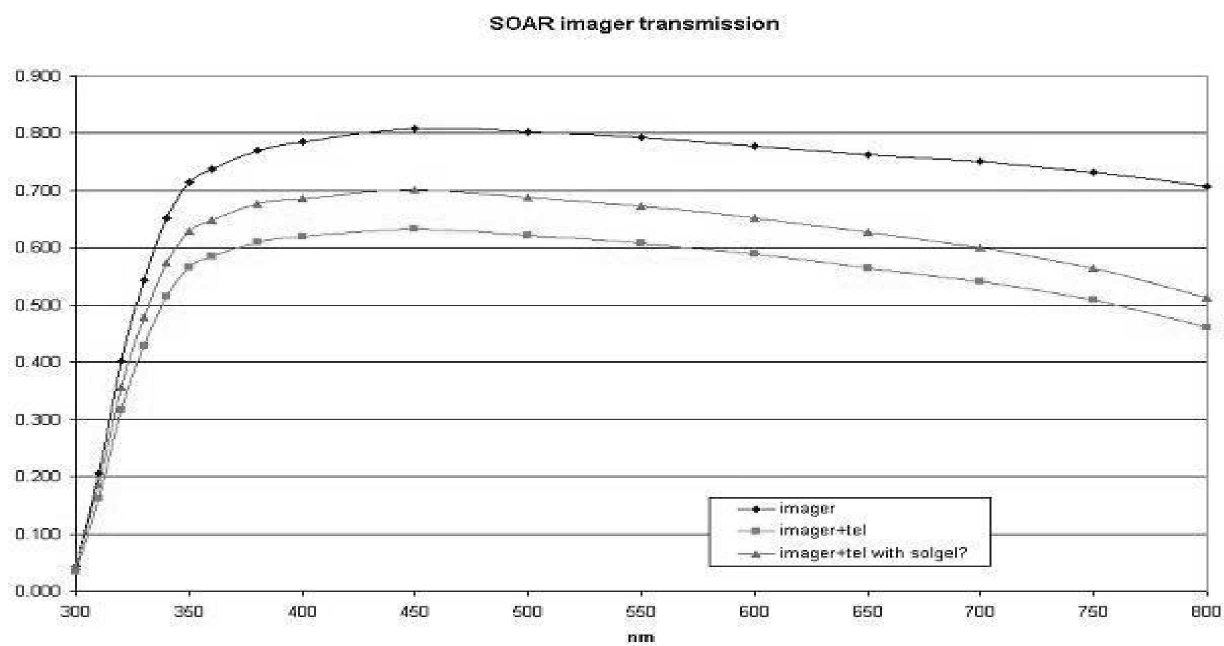

Figure 3: SOI throughput. The top trace shows the throughput of the imager optics with coatings as described in the text. The middle trace shows the effect of combining this with three mirrors, freshly-coated with aluminum. The lower trace shows the effect of not having Solgel coatings on the optics. Note these traces are calculated, not measured.

diameter is 760 microns. Assuming 40% of the incident light is reflected off the CCD and 3% off the window, there is 1.2% of the incident light spread over 2016 pixels, thus producing a scattered light level of 6E-4%. We conclude that the behavior of the optics with respect to ghost images is benign. The usual precautions of using low reflectance paint, and trapping glancing angle-of-incidence reflections with annular stops, are taken to ensure that external light paths cannot reach the focal plane.

4. INSTRUMENT DESIGN

The overall mechanical design is constrained by the need to accommodate the bulky optical system, and the necessity of incorporating a rotator. The instrument weight limit is nominally 300 kg, thus simple braced Aluminum structures allow adequate strength and allowed us to only slightly exceed (317 kg) the weight budget with all ancillary equipment attached.

Since the ADC prisms do not rotate with respect to the telescope, the rotator need only support the focal reducer optics, shutter-filter-guider box and associated assemblies mounted thereon, and the dewar. The overall arrangement in shown in Figure 4.

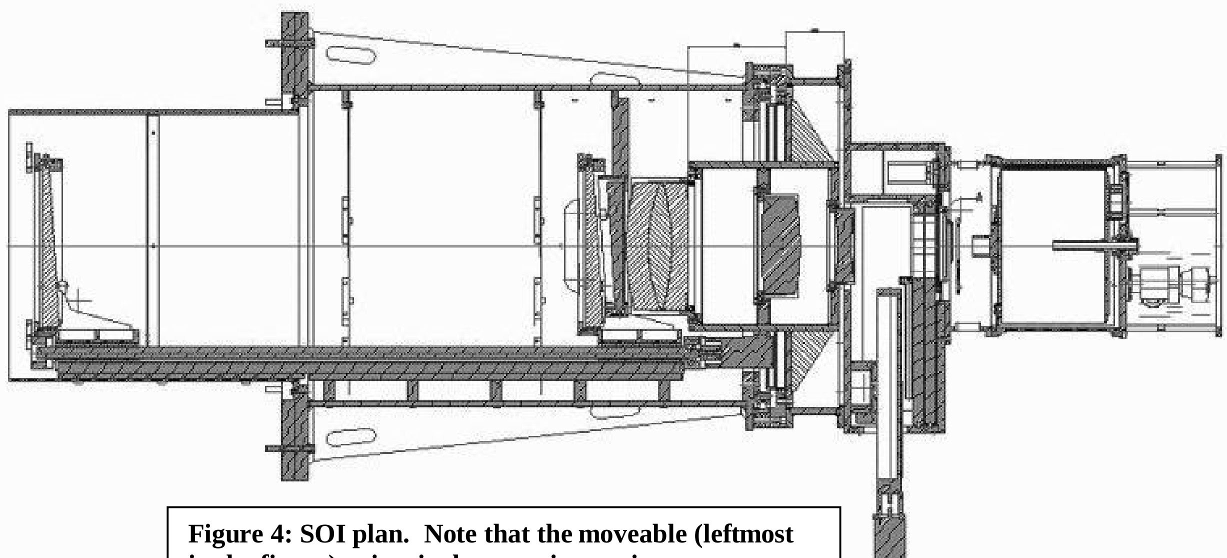

Figure 4: SOI plan. Note that the moveable (leftmost in the figure) prism is shown at its maximum extent, corresponding to zenith distance = 70 deg., and in this position extends to the inner wall of the telescope structure, well inside the instrument mounting flange

We have used Silvermax™ motors with success in several instrument projects. These "smart" servo motors, which have only a serial line and power connections, are easy to use, reliable, and are available in a range of sizes. We therefore decided to use these motors in the SOI, except for the filter wheels where we were using heritage hardware.

The SOAR Project has adopted LabVIEW for telescope, dome and environment control and specified it for the instrument control as well. In a separate contract, CTIO and the SOAR Project developed ArcVIEW, a high-level LabVIEW interface for instrument control, and this will be used for the SOI and other SOAR facility instruments.

We now describe some of the sub-assemblies in more detail.:

- ADC assembly

The two prisms do not rotate with respect to the telescope and so their mounting system is attached to the large tubular assembly (Figure 1) , which bolts to the telescope flange. One prism is fixed, the other is mounted on a Thompson linear stage, driven by a DC "smart" servo motor, controlled ultimately by the TCS, which feeds the instrument computer the zenith distance. The instrument computer then calculates the correct position to move the prism to in order to compensate for atmospheric refraction. We anticipate two modes of operation, the first is for the prism to be continuously tracking, the second is for the prism position to be set prior to an exposure, and then left in fixed position for the duration of the exposure. The stage motor is unavoidably close to the light beam, and so it is connected to a high-conductivity strap to minimize creation of a hot-spot and possible air currents.

- Focal reducer optics

All of the elements in the focal reducer are held in individual cells. The triplet is held by 8 preloaded spring elements, with hard points only in the axial direction. The compression of the spring elements was calculated to achieve an acceptable centering. The other two cells are of the "finger" type commonly used in CTIO instruments.

- Rotator and Cable-wrap

The rotator mechanism is driven by a servo motor (SilverMax(TM) QCI-23-3-E-01), directly coupled to a Harmonic Drive gear reduction, this turns a bronze friction wheel against a larger steel wheel, which houses a Kaydon 4 -point ball bearing, which is attached to the rotating part of the instrument. Position sensing is achieved by a Heidenhahn ERA 780C tape encoder located inside the bearing housing. It has a resolution of 8.164.200 counts (interpolated) per turn. The rotator has a maximum rotation speed of 0.48 deg/sec and has redundant limit switches for safety. The cable wrap consists of an IGUS energy chain system, specially manufactured for this application.

- Tip-tilt guider

The tip-tilt guider consists of a probe containing a miniature (10 mm side) right angle prism which diverts a small portion of the input beam to a second prism, where beam relay optics send it to the tip-tilt guider detector. The optics were designed by Thomas Ingerson. The prism size and probe arm cross-section are small, the latter has cross-section of only 5 mm, since they may need to occult the science beam if a guide star is desired, or can only be found, close to the field center. The probe assembly is mounted on a Parker-Daedalus XY-stage, with 0.5 µm resolution. It is also possible to fine-tune the focus independent from the telescope focus. The detector system is a thinned, quad-readout Marconi CCD-39, which is thermoelectrically cooled, and operated by an SDSU-2 controller in frame-transfer mode.

- Shutter

The shutter is a single blade "focal plane" type driven by a dc servo-motor via a cogged belt. It is low profile (4.7 mm) and high performance. Minimum exposure time is less than 200 ms, and repeatability below 0.5 ms. The drive profile is trapezoidal. The shutter has been subject to extensive lifetime tests without performance degradation.

- Filter wheels

These are slim modules that were used with the now-retired CTIO 4-m telescope prime focus imager. Each has five positions for filters up to 4-inches square and 10mm thick, with change time between adjacent positions taking one second. Positional repeatability is better than 10 microns. The nominal filter thickness for SOI filters is 8mm, and new sets of Johnson-Cousins UBVRI, Stromgren uvby, and SDSS uvgriz filters have been purchased. More specialized filters will be shared with CTIO.

- Dewar

The dewar has a significantly longer hold-time specification (30 hours) than those presently in use at CTIO. We achieved (actually exceeded by 20 hours) this requirement by building a variant of the proven CTIO dewar design, which uses liquid nitrogen (LN2) as cryogen. The thermal balance was modeled in order to determine the needed capacity. The dewar contains a highly polished aluminum can (volume 12 liters) that be filled to 50% capacity via an axial tube, which incorporates a "no ice" vent, designed by Roger Smith. A single passive radiation shield surrounds the can. All interior surfaces are highly polished, and we have seen no need to incorporate layers of super-insulation, which introduce large surface area that can trap contaminants all too easily. The LN2 can is connected to the CCD-mount area by a copper braid for which the thermal resistance can be trimmed. The CCD mount is a kinematic design, with a frame coupled to the dewar front face by G-10 stand-offs. The frame in turn carries the CCD mount and the heater, which is servoed to keep the CCD at constant temperature (within ~0.1C). The CCDs are packaged in aluminum nitride ceramic carriers, which are interfaced via a molybdenum slab which has the property of matching thermal coefficient of expansion of the carrier, along with high thermal conductivity. The thickness of the slab is trimmed to level the CCDs with respect to the dewar front face to within 10 microns. The temperature servo, for which the hardware is part of the SDSU controller, can provide constant temperature over the range of at least –70C to –125C. We anticipate the LL CCDs will be operated near a temperature near –110C.

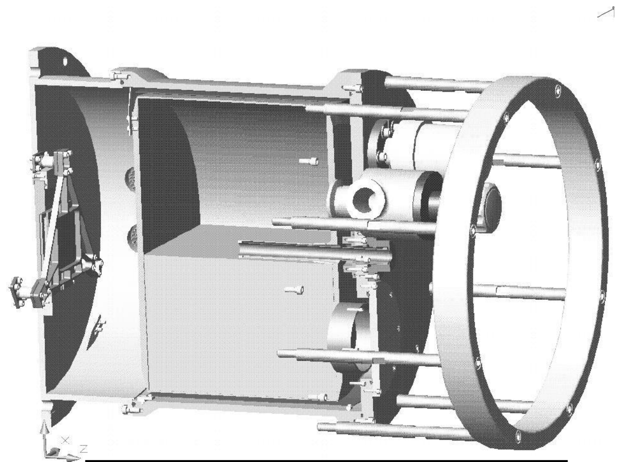

Figure 5. Dewar cut-away schematic

Temperature telemetry is relayed from the CCD mount, the LN2 can, and the vent tube area, the latter gives rapid and accurate indication when the LN2 is nearing exhaustion, well before the CCD mount temperature begins to rise. We also Monitor dewar vacuum performance, using a compact Pirani/Cold Cathode sensor and a Pressure Display Unit (PDU), both from Pfeiffer Vacuum. The output from the PDU is converted to digital format and sent via serial line to the instrument computer.

5. DETECTOR, CONTROLLER, & DATA HANDLING

The pair of detectors are Lincoln Labs CCD-20's, purchased via a consortium foundry run. The CCDs are 2Kx4K format with 15 micron pixels, thinned and back-illuminated, with surface passivated via a molecular beam epitaxy (MBE) process. The devices are built on high resitivity (7000 ohm-cm) silicon that boost the red QE and reduces fringing, and each has a split serial register with a pair of high-gain amplifiers, typically 10-15 $\mu V/e^-$. At time of writing (July 2002) science-grade devices have not been delivered.. Operating test devices have proven the MBE process, and show very high QE. A CCD with single layer blue optimized coating has QE exc eeding 75% from 300-800 nm, and a two later AR coating with broader response exceeds 75% from 350-950 nm, and peaks at 95% QE at 800 nm. CCDs with either of these coatings would be more than satisfactory for the SOI; if there is a choice the blue-optimized coating will be chosen

The CCD will be read-out using a SDSU-2 "Leach" detector controller, connected to a PC-Linux machine through a PCI board in a PCI-Linux-LabVIEW environment. Anticipated readout time is 10 seconds. The same PC will operate the instrument mechanisms except that the shutter is synchronized by the controller. Data will flow to a "reduction machine", nominally a powerful PC, but it will also be possible to send to La Serena headquarters (155 Mbs OC-2 microwave link) or elsewhere via Internet II (currently 10 Mbs, shared between Gemini, SOAR and CTIO).

The main goals of the software are to

- Read the CCD – writing images to file, supporting different modes of operation
- Provide scripting ability to allow chaining of simple operations
- Allow reliable and efficient motor communication
- Allow communication with the telescope and other systems
- Provide a friendly and efficient User Interface

The controller driver, other low-level routines, and several LabVIEW *Virtual Instruments* (V.I.'s) were developed in-house, while the ArcVIEW array control software was developed under contract by Imaginetics, Inc. The SOAR Communications Library (SCL) is a layer on top of LabVIEW and provides a reliable and flexible communications service between the components of ArcVIEW as well as with the other applications running in the same or in different machines throughout the network. ArcVIEW also provides scripting ability (GSCRIPT). ArcVIEW is described in detail elsewhere[6]; although still under development, particularly with respect to the final User GUI, it has proven powerful and efficient to use.

6. SOME SYSTEM ISSUES

In common with all modern telescopes designed with a stringent image-quality specification, handling of thermal issues for all in-dome systems must be dealt with as part of the initial design. For the SOI, these design decisions were as follows: Firstly, electronic sub-systems would be actively cooled by placing them in a temperature-controlled cabinet. Such sub-systems include power supplies for the SDSU-2 controllers and motor power supplies. Secondly, any major electronic sub-system that could not be placed within the temperature-controlled cabinet must individually be actively cooled. Both SDSU-2 controllers fall in this category. In both cases, glycol is the circulating refrigerant. Finally, the instrument itself is a large thermal mass and is well-coupled to the telescope structure. Small items such as motors and any minor electronic systems must be well-coupled to the instrument. The dc servo-motors used in this project do not have particularly high thermal conductivity between the windings and the motor mounting surface, and thus for any motor close to an optical light path special care must be taken to avoid hot spots. The ADC motor falls in this category, as discussed above.

7. STATUS

SOI is presently (July 2002) undergoing mechanical and electrical integration tests. A single engineering grade CCD is being used to check data path performance, the science grade CCDs have not been delivered and are more than a year behind their original delivery schedule. Work on the user interface GUI is continuing, with aim to have a consistent look and feel to other SOAR instruments. Late in 2002 the SOI will be installed on the SOAR telescope for flexure tests, and for final integration tests. SOAR first light is scheduled for April 2003, and the SOI is a key component for commissioning the telescope and for obtaining early science results.

ACKNOWLEDGEMENTS

We would like to thank Thomas Ingerson, Roger Smith, and Gilberto Moretto for important contributions to the SOI design. Gerald Cecil and Steve Heathcote, in their respective capacities of SOAR Project Scientist and SOAR Director have provided sage advice. CTIO draftsmen, technicians and instrument makers are thanked for their skill and dedication, without which this instrument could not have been turned from design into reality. Victor Krabbedam, SOAR Project Engineer, and Michael Warner, Systems Engineer, have dealt with telescope interface issues in timely manner.

NOAO is operated by AURA under cooperative agreement with the National Science Foundation (NSF). The Gemini Observatory is operated by AURA under a cooperative agreement with the NSF on behalf of the Gemini partnership: the NSF (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research

Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

REFERENCES

1. Sebring, T.E., Krabbendam, V.L., Heathcote, S., Wiecha, O., Schumacher, G. "SOAR Telescope Project: a progress report". SPIE **4837-09,** 2002
2. Avila, G., Rupprecht, G., Beckers, J.M. "Atmospheric Dispersion Correction for the FORS Focal Reducers at the ESO VLT". Proc. SPIE **2871**, 1135, 1997
3. Wynne, C.G., Worswick, S.P. "Atmospheric Dispersion Correctors at the Cassegrain focus", MNRAS, **220**, 657, 1986
4. Stilburn, J.R. "High efficiency sol-gel anti-reflection coatings for astronomical optics". Proc. SPIE **4008**, 1361, 2000
5. http://www.qcontrol.com
6. Ashe, M.C., Bonati, M., Heathcote, S. "ArcVIEW: a LabVIEW-based astronomical instrument control system". SPIE **4848-58,** 2002